

Energy- and environmentally efficient road management: the case of the Spanish motorway network

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Abstract

Transport is responsible for 41% of CO₂ emissions in Spain, and around 65% of that figure is due to road traffic. Tolled motorways are currently managed according to economic criteria: minimizing operational costs and maximizing revenues from tolls. Within this framework, this paper develops a new methodology for managing motorways based on a target of maximum energy efficiency. It includes technological and demand-driven policies, which are applied to two case studies. Various conclusions emerge from this study. One is, that the use of intelligent payment systems is recommended; and another, is that the most sustainable policy would involve defining the most efficient strategy for each motorway section, including the maximum use of its capacity, the toll level which attracts the most vehicles, and the optimum speed limit for each type of vehicle.

1. Introduction

Transport is widely recognized to be one of the most significant sources of greenhouse gas (GHG) emissions -in particular CO₂ emissions- which are directly related to the consumption of carbon-based fuel. The transport sector provides economic and social benefits to society as a whole, and yet it causes a number of negative environmental impacts. Within the transport sector, road transport is the mode with the highest consumption in the EU-27, accounting for 81% of the total in 2008 (Huggings, 2009). Countries are increasing their energy dependency, and consequently their impacts on not only the environment but also on the economy: oil prices, taxes, external costs, etc. For this reason, and to comply

with the Kyoto Protocol target of reducing GHGs emissions to 1990 levels, numerous policies have been implemented at both the national and international level which are designed to reduce energy consumption in the road transport sector by acting both on the planning and operational side.

Focusing specifically on the Spanish case, the transportation sector contributes even more to GHG than the EU average, and is responsible for 41% of the total CO₂ emissions (ITF/OECD, 2010). Road transport produces around 65% of total CO₂ emissions from transport (ITF/OECD, 2010). During recent decades the road network has been greatly extended, and Spain now has 20km of motorway per 1,000km², a high rate compared to the EU15 average of 15km/1,000km² (IEA/OECD, 2009). Furthermore, it should be noted that traffic from 1995 to 2009 has grown by more than 50%, and implying an increase in CO₂ emissions (Ministerio de Fomento, 2009a). Consequently, road transport is one of the key action sectors on the Spanish sustainability policy agenda, a fact reflected in the Spanish energy policy *Energy Saving and Efficiency Strategy E4 2004-2012* (IDAE, 2003) and in the recently approved *Saving and Energy Efficiency Action Plan 2011-2020* (IDAE, 2011). Its main objective is to reduce energy consumption by 20% in 2020.

The competences for the Spanish road network are shared among the state, the Autonomous Regions and to a lesser extent the cities. The network consists of 15,621km of motorways, including 3,016km of toll roads (Ministerio de Fomento, 2009a). Toll payment is moving from manual systems to advanced systems such as electronic toll collection (ETC). Nonetheless, users often tend to pay manually, causing congestion at toll areas.

This paper presents a methodology-based scenario building to assess the energy consumption of different policies for managing the motorway network in a more sustainable way. The policy options tested are management of traffic flows in parallel road sections and toll areas. The paper is structured as follows: Section 2 deals with the estimation of the road footprint as a new approach to managing roads. Section 3 describes the main variables which should be considered for motorway footprint optimization. These variables serve as the starting point for proposal of policy applications (Section 4). Various policy applications are then validated in two different case studies. Finally, results are obtained which form the basis for proposing new strategies for reducing carbon emissions in motorway networks (Section 5 and 6).

2. Road footprint: a new management approach.

The carbon footprint of a road can be defined as the total amount of CO₂ and other GHGs emitted over the full life cycle of a road (construction, operation, maintenance and deconstruction phase). However this paper deals only with the road operation that manages traffic flows emitting CO₂ due to fuel combustion. Energy consumption and emissions models are used to estimate the road footprint in the operational phase. These models provide an objective tool to evaluate measures, strategies and scenarios and can integrate the management of the energy footprint, air quality and energy efficiency into the decision-making processes (Affum, Brown, & Chan, 2003). Energy consumption -and consequently the CO₂ emissions- depends on a number of parameters such as road layout (type of road and gradient), its roughness, traffic flow distribution, congestion levels, etc. A large number of models have been developed for this purpose (Smit, Ntziachristos, & Boulter, 2010) considering road and traffic characteristics. Other models are based on applying the principles of mechanics to the calculation of energy consumption and emissions (Burgess & Choi, 2003; Janic, 2007; Zachariadis, Ntziachristos, & Samaras, 2001). They determine energy consumption in proportion to the forces that oppose vehicle motion, including rolling resistance, aerodynamic drag and air entrance resistance, and inertial and gravitational losses.

2.1. Road management from an energy efficiency approach

Transport energy consumption continues to maintain a close relationship with the growth of overall economic activity. Nevertheless, it has been shown that road transport is the largest contributor mode to final energy consumption, and is one of the greatest challenges for energy sustainability. CO₂ emissions from the road sector are 75% higher than in 1990, and this figure is set to increase in the future (OSE, 2010). The Spanish road transport sector needs to achieve significant energy and emissions savings to meet the Kyoto Protocol target. In addition to continuing to encourage efforts in fuel efficiency standards, promotion of new efficient vehicles, eco-driving, behavioral change to more efficient modes, etc., attention should be paid to road authorities and operators. They have the potential to manage the road network in a safe, reliable, economical and sustainable way. This last aspect -contributing more to sustainability and overall energy efficiency- must be taking into account in a new road management approach, specifically aiming to reduce energy consumption on the road network due to traffic flows. A new effective management for operational phases should be defined to help road authorities and stakeholders to optimize energy consumption and CO₂ impacts throughout the operational phase of the roads.

2.2. OASIS model

The *OASIS* project intends to cover this gap by developing an *Energy Footprint Model for Roads in the Operational Phase*. The main aim of OASIS is to define and to develop a model for calculating the energy footprint of the highway with regard to the contribution of traffic flow and highway design. The *OASIS* model estimates vehicle air emissions and energy consumption at the highway section level for the basic road network in Spain. It should be noted that traffic congestion is not an important issue at macro level, except the queues formed due to stop and pay at toll gates. Congestion occurs only in the metropolitan part of the network which has not been included in the study. *OASIS* model uses two different types of emissions models in order to estimate traffic flow energy consumption and emissions: COPERT IV (Ntziachristos, Gkatzoflias, Kouridis, & Samaras, 2009) and the mechanical model (Burgess & Choi, 2003). COPERT uses variable average speed to predict emissions and fuel consumption. The mechanical model estimates the energy consumption needed to overcome external forces on the toll gate under different toll payment schemes.

3. IMFO: Integrated Motorway Footprint Optimization

The total of CO₂ emissions from motorway traffic flows depends on different factors, as shown line A of the following figure. Carbon intensity depends on fuel efficiency standards, which are currently the most widely-used transport policy instrument for stimulating climate change mitigation and reducing oil dependency (Creutzig, McGlynn, Minx, & Edenhofer, 2011). Demand refers to the most rational use of the vehicle. Actions such as promoting eco-driving, modal shift to more efficient transport mode, etc., can control demand (Pérez-Martínez, Ming, Dell'Asin, & Monzón, 2011; Rodenburg, Ubbels, & Nijkamp, 2002). Finally, consumption factors depend on speed, road gradient and vehicle type, which are the main input variables for calculating the road footprint using the *OASIS* model (line B).

In order to optimize the road footprint, line C represents policy actions that influence total CO₂ emissions from traffic flows. Planners can act directly on these variables through strategies involving energy efficient road management. Recently, speed management has become a far more popular strategy for reducing road emissions as well as contributing to traffic safety (Int Panis, Broekx, & Liu, 2006; Keller et al., 2008; Keuken, Jonkers, Wilmink, & Wesseling, 2010). Road design plays an important role

at the design and building stage, since road gradient is a direct variable. Encouraging vehicle fleet renovation is another way of promoting energy-efficient road transport (Aranda Uson, Valero Capilla, Zabalza Bribian, Scarpellini, & Llera Sastresa, 2011). Finally, network management integrates all these actions and considers the combined use of all alternative O-D routes.

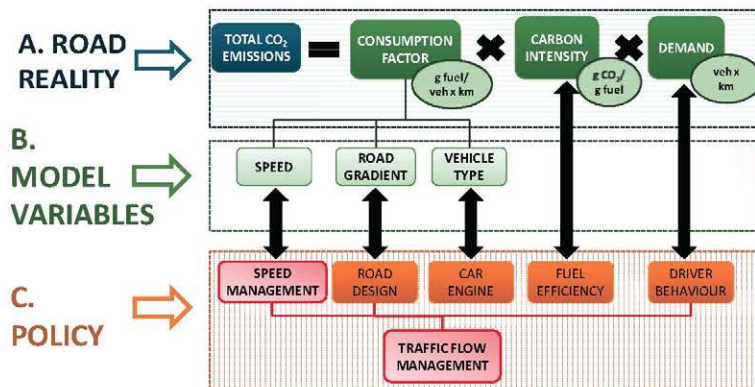


Fig. 1. OASIS model-Breakdown of CO2 emissions from traffic flows in motorway

4. Selected policy applications and case studies

This section specifies the policy applications to be considered and applied in two different case studies.

4.1. Selected policy applications

The selected policy applications are described through a scenario-building methodology. The first step in the methodology is the selection of a route which has two alternative roads: a conventional road (alternative 1) and a toll road (alternative 2). The scenario is then built taking into account three different types of management: traffic flows and speed management (Fig. 2). Additionally, there is also the option of studying the influence of the toll systems on the toll motorway.

The road footprint is calculated for each scenario, considering the total of the two alternative routes and directions. The *OASIS model*, which takes into consideration the main characteristics of different scenarios, is used for this phase. The next step is the comparison of the footprint scenarios. The reference scenario is compared to the different management proposals in order to evaluate the most energy-efficient management options. The different management strategies and scenarios are explained in Table 2.

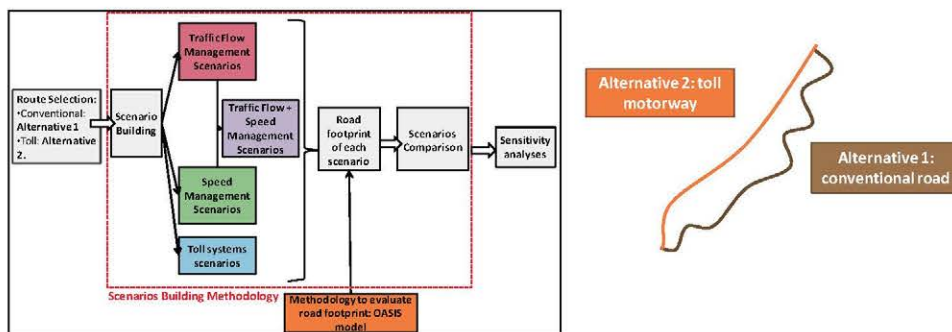


Fig. 2. Outline of energy-efficient motorway management

Table 2. Proposed management strategies

Management strategy	Scenario	Definition
	S 0	Reference scenario. All other scenarios will be compared to this.
Traffic management	S TOLL	All traffic flows are transferred to the toll motorway.
	S HDV	All heavy-duty vehicles for the conventional road are transferred to the toll motorway.
Speed management	S SPEED↓	Speed reduction on the toll motorway for light vehicles (-10km/h).
	S SPEED ↓2	Speed reduction on the toll motorway for light vehicles (-20km/h).
Traffic + Speed management	S HDV+SPEED↓	All heavy-duty vehicles are transferred to the toll motorway and there is a speed reduction on the toll motorway for light vehicles (-10km/h)
	S TOLL+SPEED↓	All traffic flows are transferred to the toll motorway and there is a speed reduction on the toll motorway for light vehicles (-10km/h).

Regarding toll management, this methodology determines the energy overconsumption of a particular stretch due to the existence of a toll area on it. This energy over-consumption is based on the different toll payment systems: manual payment, ETC and free flow payment systems. The scenario building is then carried out taking into account two different types of management: traffic flow and toll payment systems. The toll management options are detailed in the Table 3 below.

Table 3. Toll system scenarios

Management strategy	Scenario	Definition
	S 1	Toll management reference scenario. All other scenarios will be compared to this
Traffic management	S HDV ETC	All heavy-duty vehicles use the ETC payment systems
Toll system management	S ETC	All types of vehicles use the ETC payment systems
	S FREE FLOW	All types of vehicles use the free flow payment system

4.2. Case study applications

4.2.1. Case study 1: better use of toll motorway capacity.

The influence of different road characteristics and traffic flows on energy consumption and subsequent CO₂ emissions is analyzed in a case study of Pajares. Two parallel road alternatives that pass through the Cantabrian Mountains between Leon and Asturias in northern Spain. The first alternative corresponds to the N-630 conventional road; the stretch analyzed is a mountain pass which is relatively hilly and with strict speed restrictions, and has a total length of 76.8km. The second alternative is the AP-66 toll motorway. It has higher road quality than the N-630, since the hilly stretches are resolved by means of tunnel and viaducts. The total length of the study route is 77.3km. The data for the input variables are derived from the following sources: AADT and speed data are obtained from the Spanish Traffic Map 2009 (Ministerio de Fomento, 2009b). The route division by stretches, road gradient, and length are obtained from the test conducted in March 2011 with on-board recording equipment.

4.2.2. Case study 2: better use of payment technologies

To analyze the influence of different payment toll systems we have chosen a case study of a section on the AP-68 toll highway. This toll area is located at kilometer 13.6 on the AP-68 near the urban area of Llodio, between Bilbao and Miranda de Ebro. On this route the AADT is 15,628 veh/day, of which 16% are heavy-duty vehicles. The mechanical model was applied to calculate the energy demand in two toll scenarios: traditional toll payment system and electronic tag (ETC). In the case of free flow, the energy demand was estimated with the *OASIS model*. AADT and the use of each toll payment system were obtained from the Spanish Traffic Map, 2009 (Ministerio de Fomento, 2009b) and the AP-68 toll motorway concessionaire respectively.

5. Discussion of results

5.1. Case study 1 results: better use of toll motorway capacity

The outcomes show speed management strategies to be the most effective, along with the integration of traffic flows and speed management. Conversely, scenario *S TOLL* shows an increase in fuel and energy consumption and CO₂ emissions. This is justified by the fact that although toll motorways are better quality, their speed is greater compared to conventional roads, thus increasing the road footprint. The comparison of each scenario with the reference scenario *S0* is shown in Fig.3. Under scenarios *S SPEED↓* and *S SPEED↓2*, the greater the speed reduction, the greater the changes in emissions. A speed reduction of 20 km/h leads to saving of almost 5.5% of CO₂ emissions per year with regard to the reference scenario. Nevertheless, speed reduction leads to an increase in travel time. Transference of heavy-duty flows to toll motorways produces savings of less than 1%. However, transference of heavy-duty flows to toll motorways with a speed reduction for light vehicles on toll motorways produces emissions savings of nearly 4%. It should be noted that *S HDV+SPEED* is the most energy-efficient scenario, although CO₂ emissions and fuel consumption are smaller than *S SPEED↓2*. This is justified by the fact that HDV have been assumed to use only diesel fuel, which is more energy efficient than petrol.

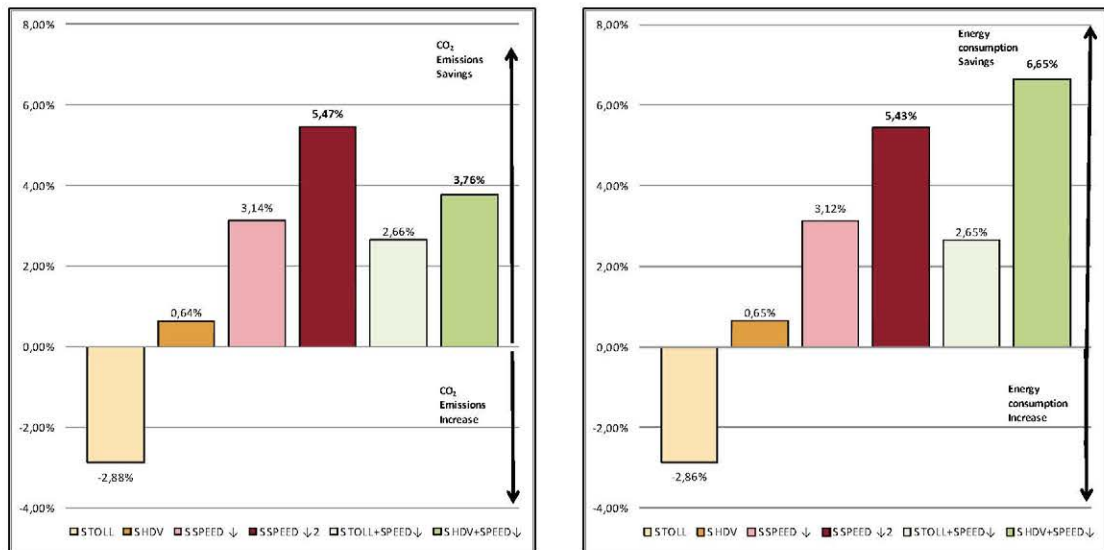


Fig. 3. (a) CO₂ emissions and (b) energy consumption savings (%) in a comparison of scenarios

5.2. Case study 2 results: better use of payment technologies

In the second case in the present study, two different toll systems have been analyzed: traditional toll and ETC. The main difference between them is the method of payment. The traditional toll is split into three phases: deceleration (2m/s^2), stopping to pay fees (15 seconds) and acceleration (2.5m/s^2) and ETC, where commuters merely have to slow their cars down to a certain speed (8.3 m/s) to pay, instead of bringing the vehicle to a complete halt. The use share of each one of these toll systems in Llodio is 74% for traditional tolls and 26% for ETC. Regarding vehicle categories, the use share is 21% for light vehicle ETC versus 79% for traditional tolls; and 56% ETC for heavy-duty vehicles ETC versus 44% for traditional toll payment. Lastly, energy consumption and subsequent CO_2 emissions were estimated in the free flow system without the use of toll booths, and therefore without reducing vehicle speed. The results for CO_2 emissions and energy consumption per vehicle kilometre by vehicle are shown in Fig. 4(a) and the savings by type of vehicle for all toll scenarios appear in Fig. 4(b).

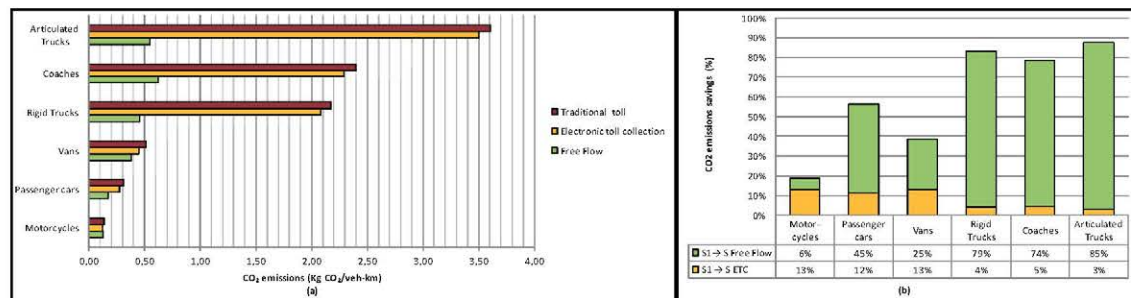


Fig. 4. (a) CO_2 emissions (Kg $\text{CO}_2/\text{veh-km}$) and (b) CO_2 emissions savings (%) in different toll scenarios

The comparison among the different vehicles clearly reveals that the greatest savings are produced in HDV, so vehicle mass parameter significantly affects CO_2 emissions. The most significant savings are produced in the free flow scenario, with 68% savings in CO_2 emissions versus 4% in the *S ETC* scenario, and only 1% in the *S HDV ETC* scenario. The main reason is that in both scenarios there are different movement stages (deceleration, a stop in one case, and acceleration), while in free flow vehicles are not required to reduce their speed. On the other hand, congestion produced by the manual payment at the toll gate (S1 scenario), produces an increase of energy consumption and CO_2 emissions by 16%.

5.3. Sensitivity analyses

As was shown in Fig. 1, the consumption factor depends on three main variables: speed, road gradient and vehicle type. The sensitivity analysis of the road footprint model reveals which factor is the most influential for energy consumption, as well as for CO_2 emissions. It has been carried out for the S TOLL scenario where all traffic flows pass through the toll motorway. A wider analysis has been done including all main parameters at toll gate (Pérez-Martínez et al., 2011)

The first step is to consider the parameters which can be modified in the operational phase: speed and traffic flows. Sensitivity to speed is the most important result. Fig. 5(a) shows that CO_2 emissions are most sensitive to speed in the operational phase. When speed was reduced by 20%, CO_2 emissions decreased significantly from 106 thousand to 93 thousand of tons per year. A thorough analysis of speed parameters showed that speed for light vehicles is more sensitive than speed for heavy vehicles, which means that applying speed reduction management strategies to light vehicles produces a greater reduction

in CO₂ emissions and consequently greater efficiency than by applying these strategies to heavy vehicles (Fig. 5(b)).

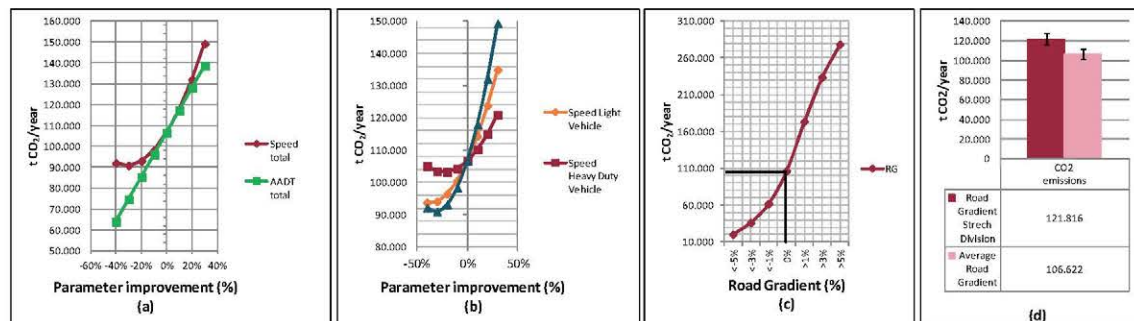


Fig. 5. Sensitivity analyses: CO₂ emissions with parameter changes under scenario S TOLL.

The sensitivity results for road gradient parameters are shown in Fig. 5(c). When the road slope increases from 0 to 3%, CO₂ emissions rose from 106 thousand to 233 thousand tons per year, as vehicles consume a lot more energy on unfavourable slopes. As the road gradient is a difficult parameter to change in the operational phase, it should be considered during the design and building stage of the motorway project. Fig. 5(d) shows that there is a 14% difference between the calculation of CO₂ emissions considering the route division on homogeneous stretches and considering average characteristics. In conclusion, the road gradient is an important factor that should be defined with care.

6. Conclusions and recommendations

Energy efficiency is of key interest to transportation stakeholders. It improves global warming, health impacts and fossil fuels dependency. With relatively easy measures, improvements can be made in fuel consumption and the energy footprint depending on the measures scenarios. Cooperative implementation, where vehicles, technology and management systems actively interact, have the potential to further improve energy efficiency.

This paper investigates the effect of implementing different motorway management strategies and toll payment systems on energy consumption and CO₂ emissions. An energy-efficient management methodology was developed for traffic flow on the Spanish motorways, capable of addressing policy measures and strategies in different situations. The proposed methodology suggests a procedure to manage traffic flows on the Spanish network from the point of view of energy efficiency, and is supported by a model to evaluate the road energy footprint. Moreover, this methodology has been analyzed and validated by application to two different case studies. The research has considered traffic flow efficiency by promoting energy-efficient alternative routes which could reduce energy consumption and emissions at very low cost. The case study revealed that the most effective traffic flow management is the reduction of speed on motorways for cars, which was also proved in the sensitivity analyses, with reduction of some 5.5% of CO₂ emissions. Furthermore, heavy-duty vehicle flows have also been successfully transferred to alternative high-quality motorways, reducing energy consumption by 0.65%. With regard to toll area management, it has been proved that the use of new technologies would reduce energy consumption and CO₂ emissions up to 68% and improve other factors such as travel time. Future increase of traffic flows could produce regular congestion if road capacity is overpass. Then it would be necessary to improve the OASIS model since emission factors of traffic in congested situations are twice as high as those with free-flow traffic (Keuken et al., 2010).

Finally, some recommendations can be obtained from this study. In view of the fact that users choose the route with the lowest perceived generalized cost –including time costs–, the *OASIS model* could be used to improve energy efficiency in traffic flows in Spain, encouraging heavy-duty flows to use more efficient motorways through policies such as subsidizing part of the price in order to obtain flexible toll rates; offering guidelines for planning routes which allow the reduction of fuel use; and indicating shorter, safer and more sustainable routes with less traffic disruption.

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